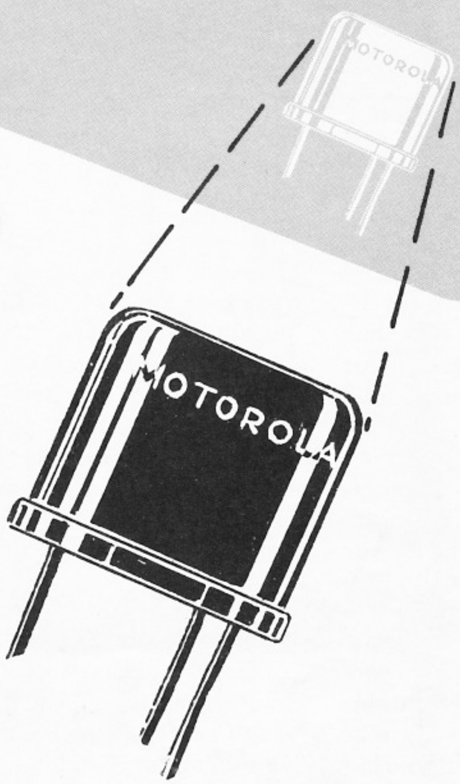
[redacted]

THE TRANSISTOR- A Reliable Component

By
HUGO KORN
Project Engineer
Transistor Circuit Research Section
Motorola, Chicago, Ill.



MOTOROLA INC.
Communications and Electronics Div.
4545 West Augusta Blvd., Chicago 51, Ill., SPaulding 2-6500

THE TRANSISTOR- A Reliable Component

By
HUGO KORN
Project Engineer
Transistor Circuit Research Section
Motorola, Chicago, Ill.

A Simple Description Of A Control Device That Is Receiving Increased Attention From Industry

The transistor, since its invention about seven years ago, has been hailed as a contender for the position that the vacuum tube has held for so long a time. It is the purpose of this paper to explain, in a simplified manner, the mechanism of transistor action and to justify some of the optimism with regard to the predicted superior reliability of the transistor as compared to the vacuum tube. In the seven years of its existence, this revolutionary device has reached a state of development far greater than that of its predecessor, the vacuum tube, considering the relative age of each. In fact, some of the early designs are now obsolete and specialized types are rapidly being developed to fulfill specific application needs. Some typical examples of designs for particular applications are shown in Fig. 1 where, from left to right, we see a transistor specifically designed for medium power audio applications, one for radio frequency amplification, and one on the far right for high power audio work.

This rapid and varied development is even more outstanding since, in addition to acquiring an understanding of the basic electronic action involved, a whole new field of solid state physics and metallurgy had to be expanded to deal with the theoretical and practical problems of this new and promising device. For this reason our knowledge of the device, at present, is far from complete and our predictions for the future are probably somewhat conservative although at first glance they might appear just the opposite.

The transistor, like the vacuum tube, is a control device and performs approximately the same functions, but in a different manner. Whereas the vacuum tube accomplishes its control function by controlling electrons in a vacuum, the transistor performs its task by controlling electrons in a solid. In its simplest form, the transistor controls a larger output current with a smaller input current by modulating the resistivity of the solid material. In fact, the initial development was an outgrowth of the study of nonlinear resistances in the Bell Laboratories.

The transistor is a worthy rival for the vacuum tube in that it can perform a majority of the same tasks with the following advantages:

The transistor is extremely rugged. It consists of a solid block of material that will stand extreme shocks. This is to be contrasted with the fragile, by comparison, construction of the normal vacuum tube. From the reliability standpoint, transistors promise unbelievably long life. The term is phrased in this manner because their predicted life is longer than the devices have been in existence. There have been some unfortunate cases of short lives, but these cases are steadily being submerged under the constantly mounting pile of evidence of amazing reliability. In any case, failure does not occur in the sudden and unpredictable "burn out" as in a vacuum tube, but rather in a very extended and slow deterioration. As the art of solid state physics progresses, we may eventually see a time in which the problems of even the slow deterioration have been solved.

In addition to the reliability feature, these units have an appeal to the designer in terms of their small size and low power consumption. The size of the active portion of the transistor is comparable to the eye of a needle, as shown in the internal view of a typical unit in Fig. 2. In addition, since they have no filament, a rather significant contribution to the heating of the equipment is removed. Furthermore, they are able to perform amplification of an audio signal of the order of thousands of times in power while only consuming a few milliwatts and all of this at the instant the switch is turned on, since there is no warm up time. By comparison with the low power vacuum tube, the transistor offers the advantage of a much smaller, more rugged, phys-

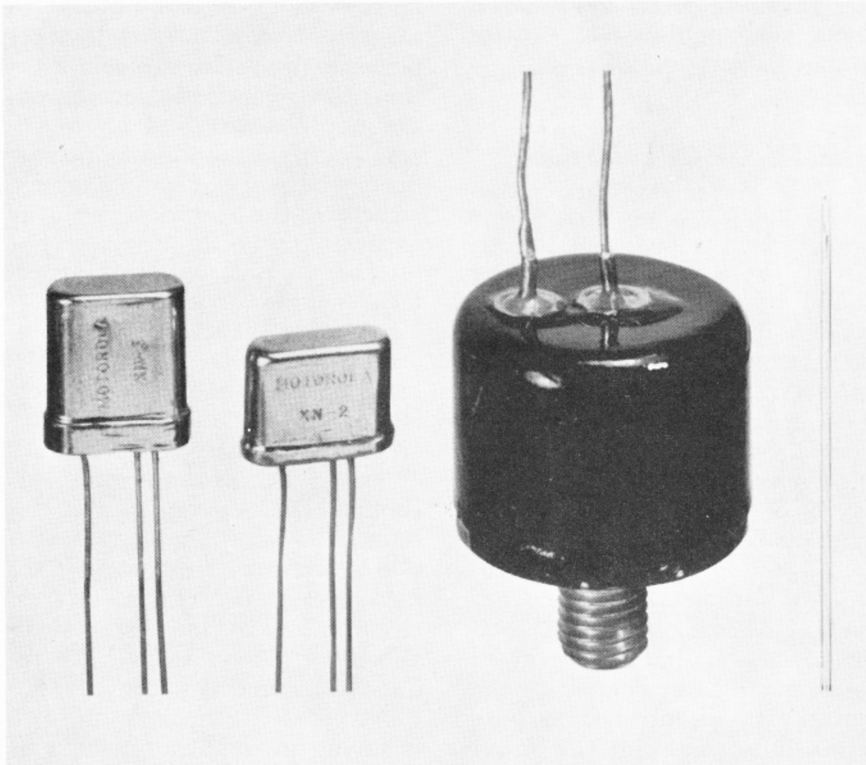


Figure 1.
EXAMPLES OF TRANSISTORS FOR SPECIFIC APPLICATION
(Compared in size with needle shown at right)

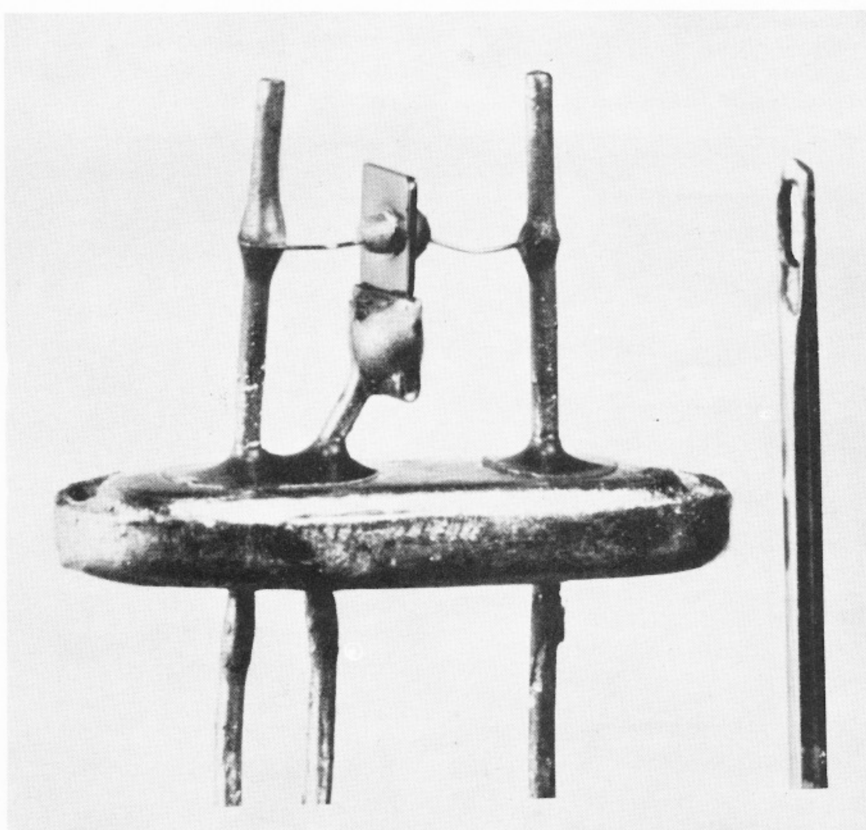


Figure 2.
INTERNAL STRUCTURE OF A FUSED-JUNCTION TRANSISTOR

ical package with a reduced power consumption and greatly extended operating life.

THEORY OF OPERATION

The operation of this device depends on the fact that the resistivity of a material can be altered by a current flowing through it. This is not due to the heating effect as in a thermistor, but rather depends on some basic peculiarities of a class of materials we call semi-conductors. The term, descriptive though it may be, is only relative, since all materials can be made conductive by subjecting them to disturbances of sufficiently high energy level. However, some appreciation for the magnitudes involved can be obtained by comparing the resistivity of intrinsic or pure germanium, perhaps the most common semi-conductor, with that of copper, a good conductor, and polystyrene, a good insulator. Pure germanium has a value of 60 ohm-cm compared with the value for copper of 1.7×10^{-6} ohm-cm and for polystyrene of 10^{18} ohm-cm. As can be seen, the value for these common substances range over 24 orders of magnitude. In addition to their place in the resistivity classification, the semi-conductor materials are characterized by a decrease in resistance with increasing temperature. From its atomic structure, the material would be expected to be an insulator but internal thermal agitation generates enough carriers to make it a conductor even at room temperatures. Of course, elevating the temperature increases the thermal agitation with consequent increase in conductivity. This fundamental behavior of the semi-conductors has given them a bad reputation with regards to operation at elevated temperature, but the development of stabilizing circuitry and the increasing availability of silicon units have reduced its importance to a negligible degree. Silicon, although behaving in the same manner as germanium, does so to a much reduced degree at any given temperature.

In addition to the normal well known conduction process by electron flow, the semi-conductors can also support conduction by movement of electron deficiencies or "holes". A rather involved explanation with references to quantum mechanics is necessary to fully justify this statement. For now, suffice it to say that, although all conduction processes take place by electron movement, the convenient fiction of positive charged "holes" makes an explanation of transistor action possible on a plane that can be easily grasped by others than the solid state physicist.

We characterize the type of semi-conductor by the sign of the carriers normally present. This can be altered by a process known as "doping", wherein traces of elements from the fifth and third column of the Periodic Table of Elements are added to the semi-conductor material which appears in the fourth column. The significance of the word traces can be seen from Fig. 3, which shows how the resistivity of the basic semi-conductor material can be altered by infinitesimal amounts of impurity materials. If the impurity added is from the fifth column such as Arsenic, Antimony, or Phosphorus we have an excess of electrons and we call the material N-type to signify the net negative charge of the carriers. Similarly, if we "dope" with a material from the third column, such as Boron, Aluminum, or Indium, we have a net deficiency of electrons or a net postive charge for the carriers and the material is called P-type. The resistivity of any sample depends upon the sign and number of majority carriers. Since the resistivity is such a sensitive function of impurity concentration, the manufacturer usually purifies the basic material to the intrinsic state and then adds impurities to bring it down to a controlled value of resistivity. The resulting material is still considered germanium, since the materials that have been added to create the alloy are infinitesimal in number. This purification and refinement is the principal factor in the high cost of the raw material.

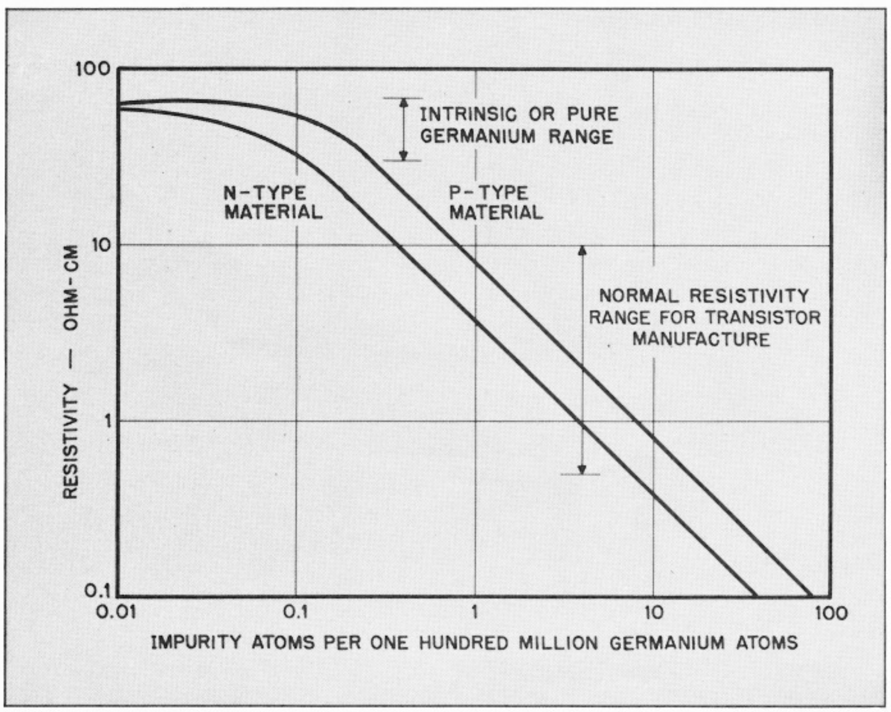


Figure 3.
RESISTIVITY VS IMPURITY CONCENTRATION GERMANIUM AT ROOM TEMPERATURE

If a piece of semi-conductor material doped into the N state is placed in intimate contact with a piece doped in the P state, the result is a P-N junction. This constitutes a rectifier since the value of the current that will pass through the junction is dependent upon the polarity of the voltage applied to the junction.

This can best be explained with the use of Fig. 4. Here we have a P-N junction with the electron carriers represented as minus signs and the holes as plus signs. The usual rules of electricity apply, namely opposites attract and likes repel. If the junction is biased as in Fig. 4 the carriers will be attracted across the junction and a current will flow provided the bias is greater than the work function which is usually a matter of millivolts. The effect can be visualized by considering the carriers and junction in terms of movable charges and a potential hill as shown in Fig. 4. The positive charges can easily run down the hill and the negative ones ascend the hill. The slope of the hill is dependent upon the sign and magnitude of the applied bias. In this case, the slope of the hill is such as to favor the flow of carriers and current. If, however, the bias is reversed, the carriers will be attracted to the electrodes as in Fig. 5, and a region will be left at the junction that is devoid of carriers. This will be semi-conductor material in a pure or intrinsic state and constitutes a very high resistance. The current will be practically zero, since it is possible only due to the thermal generation of carriers and the junction resistance will be that of a rectifier in the backward direction. If we employ our hill analogy again we see that the slope of the hill has been reversed so that it is practically impossible to have any movement of the carriers if we remember that the positive charges cannot climb the hill and the negative ones cannot fall down the hill.

If we now make a "sandwich" out of alternate layers of P and N material we will have a transistor. The order in which the junctions are assembled identifies the transistor as to whether it is N-P-N or P-N-P, Fig. 6 illustrates such a sandwich of P-N-P type. Here the left hand junction is a P-N type and biased in a forward direction so that current is flowing. The right hand N-P junction is reversed biased so that the junction considered by itself would have negligible current flowing. However, the addition of the left hand junction changes the picture considerably.

The alternate layers of semi-conductor material are called, from left to right, emitter, base, and collector. The emitter serves

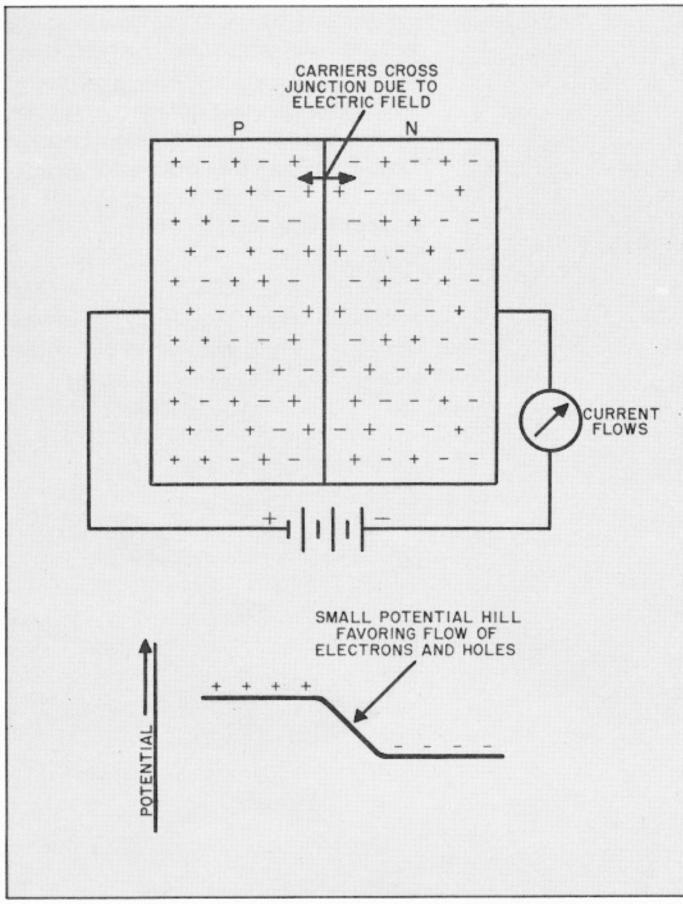


Figure 4.
P-N JUNCTION WITH FORWARD BIAS

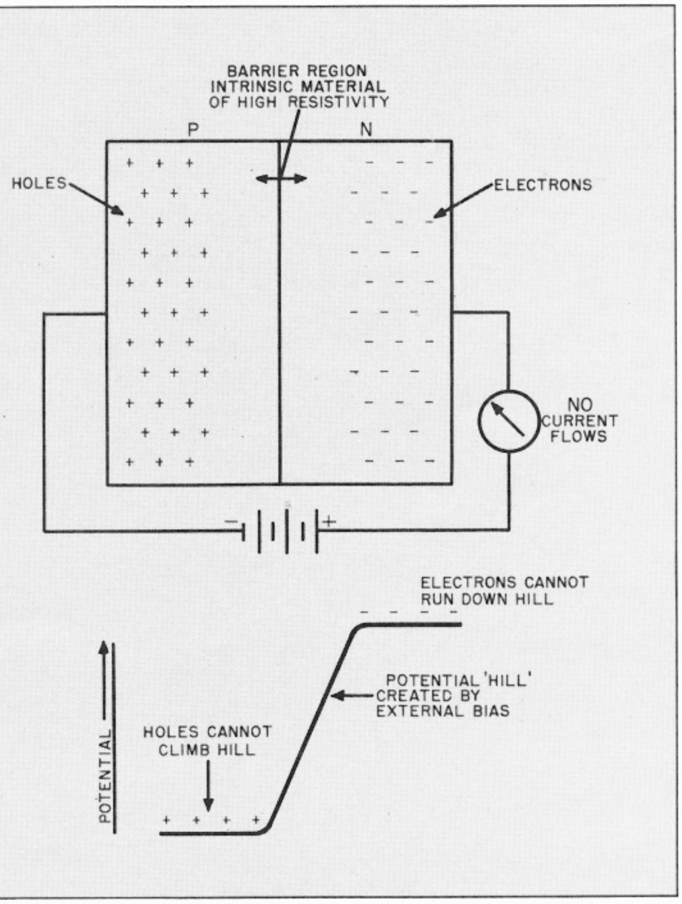


Figure 5.
P-N JUNCTION WITH REVERSE BIAS

as a source of charged carriers, in this case holes. These pass into the base region where they are considered minority carriers since they are of a sign opposite to the normal value. Some of these combine with the negative carriers in the base but others diffuse to the barrier layer between the base and collector. Here they are subjected to the field from the collector supply and are swept into the collector circuit. In this manner, the input current, by placing holes in the base layer, has enhanced the collector current. This can be seen also from the potential hill analogy. Here, positive charges are swept over the small hump to the base region. If they drift near the base-collector junction, they rapidly fall down the hill to the collector. This is only possible when the positive charges are in the base region since the negative ones cannot ascend the potential hill.

As might be expected, the presence of both electron excesses and deficiencies in the same location, will lead to some recombination; that is, some of the electrons will fill up some of the holes in the base region. Also, the current passing across the emitter-base junction is composed of both types of carriers. For good transistor action, we would like the current to be carried primarily by the minority carriers of the base region which, for the case of the P-N-P transistor, would be holes. The ratio of hole current to total current is termed emitter efficiency and is always close to, but less than unity. For this reason, as well as recombination, we always get a smaller increase in collector current than we do with emitter current as shown in Fig. 7. The ratio of output to input current is called the current gain or alpha and is measured with the output short circuited. For a junction transistor, in its normal operating range, alpha is always less than unity.

THE TRANSISTOR AS AN AMPLIFIER

As we are interested in using the transistor as an amplifying or control device, we expect it to have gain. In this connection, we can only speak of gain in terms of power gain. If we are to get power gain from the grounded base circuit configuration shown in Fig. 7, it is necessary that the impedance levels of the input and output circuits differ. If, as is normally the case, alpha is very close to unity (0.95 to 0.99) then the gain is almost exactly the ratio of the output to input impedance. Since the transistor has a low input impedance, due to the forward biased diode, and a high output impedance due to the reversed biased diode, the conditions for amplification naturally arise if the terminations are matched impedances.

It should be noted that the base current is the difference of the input and output currents and, as such, is rather small in comparison with them. If we can control the base current rather than the emitter current, we then have the added possibility of current gain as well as impedance change as a mechanism for gain. Fig. 8 shows such a circuit configuration, which is called the common emitter configuration. Here, a new value of current gain is defined as beta (β), which is larger than unity. Since we still have an impedance level change from input to output, we find that the added current gain gives us additional amplification. This feature makes the common emitter circuit the most useful circuit for transistor applications.

Figs. 7 and 8 indicate the transistor as being constructed of pieces of P type material embedded into the N type base.

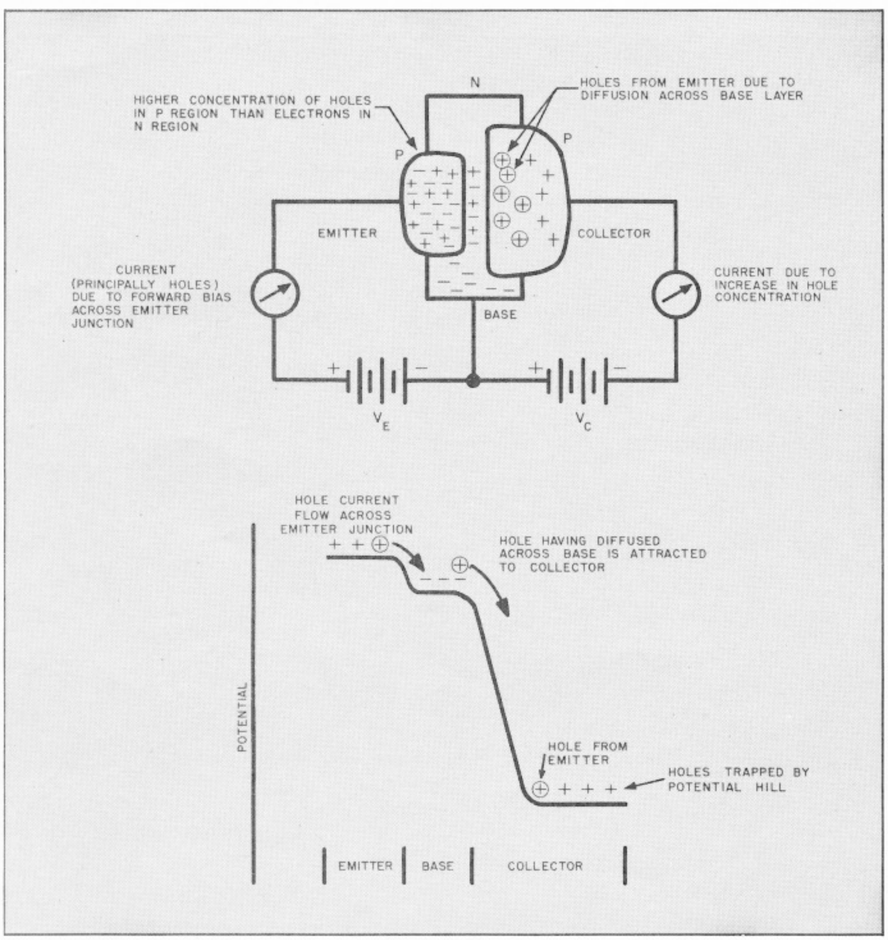


Figure 6.
P-N-P JUNCTION TRANSISTOR ACTION

This is representative of the most common manufacturing technique in use today. This type of construction is called a fused junction since the P material is actually fused into the base to obtain the intimate contact necessary for the creation of the junction.

MANUFACTURE

In manufacture, the germanium or other semi-conductor material is first refined to a high state of purity so that there is less than one impurity atom for each one hundred million germanium atoms. The material is then doped to obtain the desired resistivity and the material solidified in the form of a single crystal. This crystal is then cut into pieces approximately the size of the finished base and carefully etched to obtain a clean smooth surface. Pellets of a third column impurity, such as indium, are positioned on each side of the base and the entire assembly placed in a furnace. The depth of penetration of the indium and the resulting base thickness are determined by the time and temperature of the firing. The P type emitter and collector are formed by the indium alloying with the germanium. The finished units are etched to remove any metallic shorts from indium to germanium on the surface and the units mounted and sealed in an inert atmosphere. It is apparent that the quality of the finished product is dependent upon the uniformity of the material since the depth and shape of penetration must first be determined by a trial and error process and the results used as a guide for future efforts. The collector pellet is deliberately made larger than the emitter to gather in a large number of carriers that are drifting through the base region.

APPLICATION

The transistor is not a direct replacement for the vacuum tube in the sense that they can be traded in the same socket. The transistor requires specially designed circuitry to fully exploit its potential. It differs from the vacuum tube in that it must be considered as a four terminal network as shown in Fig. 9, where the input is definitely a function of the output. We normally consider that the grid circuit of a vacuum tube is an open circuit and that the power input is negligible. This is not true for the transistor where we must supply a power input for a given output.

Fig. 9 is intended to show the correspondence between the vacuum tube and transistor in terms of the action of the elements. That is, the emitter is analagous to the cathode, the base corresponds to the grid and the collector performs a function similar to that of the plate. Thus we say that the common base connection has similar properties to a grounded grid vacuum tube, the common emitter is analagous to the grounded cathode vacuum tube and the common collector circuit similar to a grounded plate vacuum tube or cathode follower in that it could have a very low output impedance and high input impedance.

Since we are interested in transferring power, impedance matching is a very important part of a circuit design. This is further complicated by the fact that

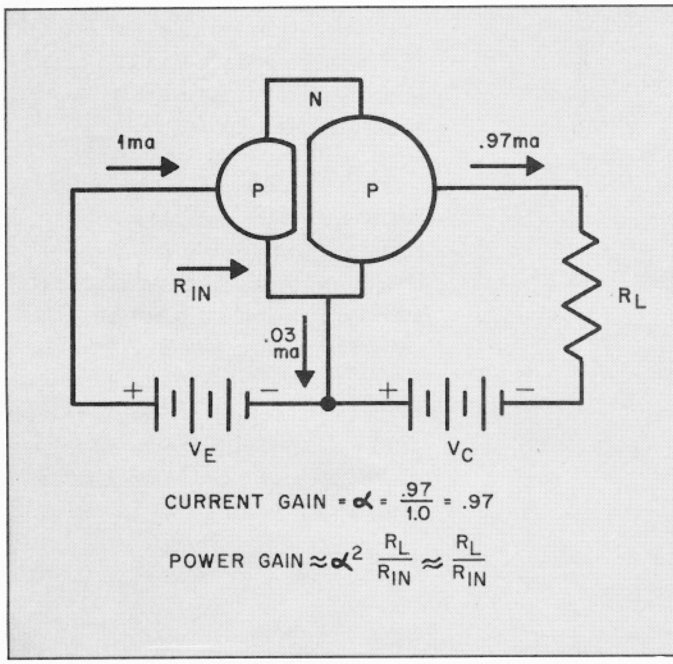


Figure 7.
GROUNDED BASE TRANSISTOR AMPLIFIER

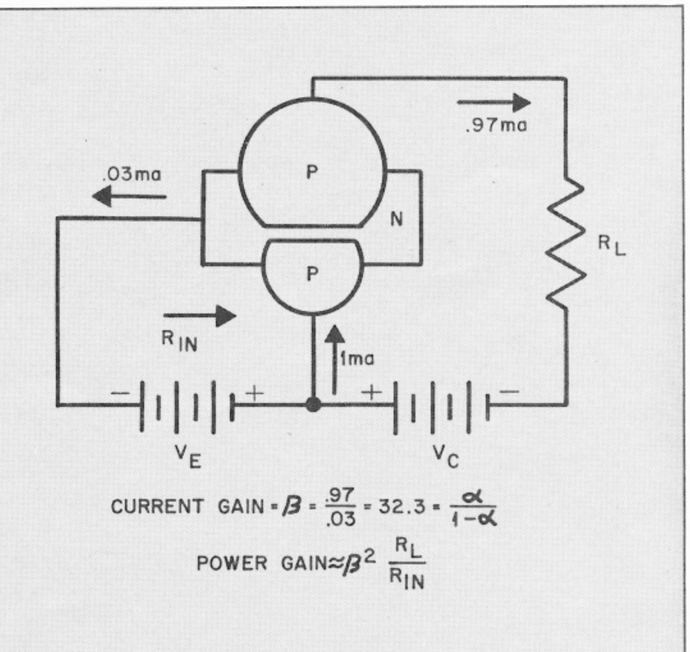


Figure 8.
GROUNDED EMITTER TRANSISTOR AMPLIFIER

the input impedance of the first stage of a multi-stage amplifier is somewhat dependent upon the value of the load impedance at the output end of the amplifier. This occurs because the impedance between the input and output circuits has an element common to them both. This effect can be greatly reduced by the proper use of feedback known as neutralization. Transistors have nearly ideal collector characteristics in that they are parallel equidistant straight lines. This permits collector swings with input signal from almost zero current to almost zero voltage condition. The limitations are only the back current of the collector diode with no emitter input (Ico) and the curvature of the characteristics at low collector voltages. The theoretical efficiency of a Class A amplifier is 50% and a transistor is able to operate in this condition at about 49% efficiency. Power gains on the order of 10,000 times or 40 db per stage can be obtained with power supply drains of a few milliwatts. This feature makes the device a natural for low power portable applications such as hearing aids.

Special construction techniques, primarily concerned with dissipating heat from the collector junction, have made possible units of higher power rating. Such a unit is illustrated in Fig. 10. Here the collector junction is fastened to the brass shell by a material of good thermal conductivity. The brass shell is intended to be fastened to a heat sink, such as a chassis, by a threaded stud. In this manner power outputs on the order of five to seven watts per unit have been obtained.

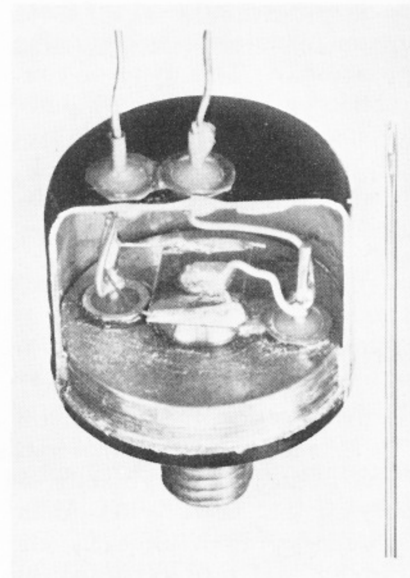


Figure 10.
CUT-AWAY VIEW OF A HIGH POWER TRANSISTOR

SUMMARY

In summary we may say that transistors offer the advantage of extremely efficient use of the available power supply, even at high power levels. Their predicted long life is dependent on the definition of useful life, since a transistor is not subject to such violent disturbances as a sudden opening of a filament and consequent sudden cessation of operation. Rather, a transistor is subject to a gradual deterioration over a period of years under normal operation, and even this effect will be reduced as the fundamental mechanism of its action are subjected to further study.

The absence of high temperatures and the extremely rugged construction should offer reliability advantages for unattended communication or control applications. Some problems have been encountered in the past due to manufacturing difficulties and quality control. Now, however, more than one and one half million units are in use in hearing aid applications alone and more applications are being marketed everyday. In short, the vacuum tube has met a contender for its position that is a worthy challenger.

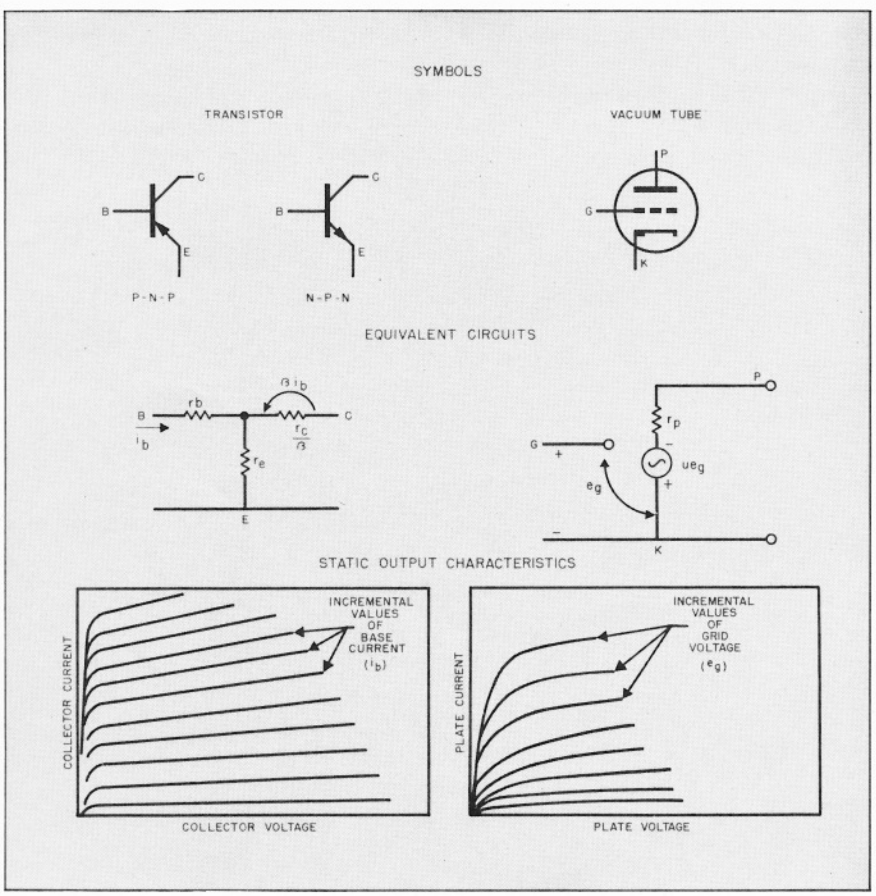


Figure 9.
COMPARISON OF TRANSISTOR AND VACUUM TUBE